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Development of magnetoresistive thin film sensor for magnetic field sensing applications

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Abstract. Recently, nano-dimensional magnetic thin film and multilayer structures have attracted a great deal of interest due to the possibility of unique and desirable magnetic properties. Our research into magnetic thin films is primarily focused on the growth and properties of such structures on Si to develop the magnetic sensors for field sensing applications. Thin films of permalloy ($Ni_{81}Fe_{19}$) were deposited on silicon substrates using Ultra High vacuum (UHV) sputtering system (~ 5 x 10^{-9} mbar). To achieve the negligible hysteresis and high thermal stability of these films, the magnetic and structural properties were optimized by (1) varying thicknesses of magnetic films, and (2) post annealing at various temperatures. Optimized films were then patterned to study the device output characteristics to know about their sensitivity and we achieve the sensitive of the order 45 μV/G/V which is equivalent to any commercially available magnetic sensors. These anisotropic magnetoresistive (AMR) based sensors are very useful for further development of navigation compass to use in strategic sectors for the self reliance of our country.

Keywords: AMR, hysteresis, NiFe.
PACS: 75.30.Gw;75.70.-i

INTRODUCTION

Thin film magnetoresistive (MR) sensors are widely used in various applications and have a significant impact over the past fifty years in many different key technological areas due to higher sensitivity, cost effective and small in size. MR sensors are usually divided into two categories based on Anisotropic Magnetoresistive (AMR) and Giant Magnetoresistive (GMR) sensors. This classification results from the different mechanisms and features of these effects. In this report, we have optimized the process parameters for the growth of magnetic thin films based on AMR properties and also fabricated devices using these films.

EXPERIMENT

Highly pure ferromagnetic magnetic thin films of $Ni_{81}Fe_{19}$ (i.e., permalloy) have been deposited on the SiO_2/Si substrates (dimensions: 20 mm×20 mm), while the tantalum (Ta) was used as buffer and cap layers. To get the high purity permalloy thin films, the depositions of these films were carried out using a Ultra High Vacuum (UHV) sputtering system at a base pressure of 10^{-9} mbar. The structural characterization of these coatings was carried out by X-ray diffraction (XRD) and Transmission Electron Microscopy (TEM), while the magnetic characterization was carried out by magnetotransport system and Vibrating Sample Magnetometer (VSM). Effect of in-situ annealing temperature in the range of 150 to 500 °C was also studied.

Results and Discussion

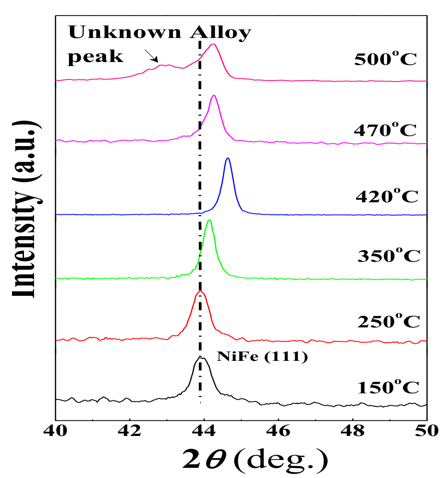

FIGURE 1. Effect of heat treatment in vacuum on the X-ray diffraction peak position of NiFe (111) reflection planes.

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Fig. 1 shows the XRD pattern of the films with structure Ta(10nm)/ $Ni_{81}Fe_{19}$ (50 nm) /Ta (10nm)/Si annealed in vacuum at temperature from 150-500°C. The main peak observed in XRD data was at 2θ = 43.89°. This peak correspond to (111) reflection plane of the Face Centered Cubic (fcc) crystalline structures of the permalloy thin film. For the films heat treated at temperatures above 350 °C, (111) peak was shifted slightly at higher 2θ. Furthermore, at 500 °C, an extra unknown peak was observed. Fig. 2 shows the variation of the grain size of the films (i.e. calculated using Debye Scherre formula) with respect to the annealing temperatures. Up to 420 °C, increase in the grain size from 15 nm to 25 nm was observed, while from 470 to 500 °C, a sharp decrease in the grain size (i.e., 23.31 to 14.76 nm) was observed.

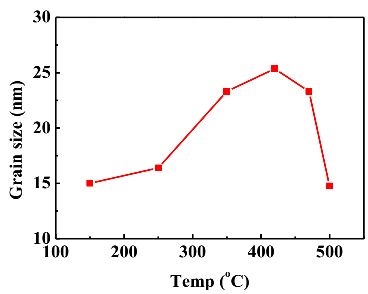

FIGURE 2. Variation of NiFe garin size with temperature

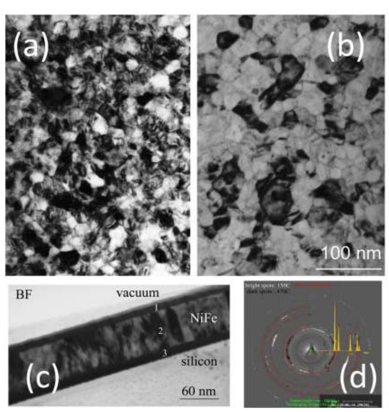

FIGURE 3. plane-view micrographs of the films vacuum annealed at 150 and 470°C, respectively (a-b), corresponding cross-section micrographs (c-d) and their selective area diffraction micrographs

Transmission electron microscopy was performed for the micro-structural studies of the Ta/$Ni_{81}Fe_{19}$/Ta/Si thin films vacuum annealed at 150 and 470 °C, respectively. Figs. 3 (a-d) show the 2-dimentional plane- view micrographs, the bright field cross-sectional transmission electron microscopy (XTEM) micrographs and the selected area diffraction micrograph (SED) of sample annealed at 150 and 470 °C in vacuum for 1 hour.

From the plane-view micrograph as shown in Fig. 3(a), it is confirmed that the lateral grain size of the NiFe film annealed at 150 °C was approximately 15-17 nm. Increase in grain size to 23 nm was further observed by annealing at 470 °C. From the XTEM micrograph, the thickness of the Ta as a buffer layer (1) and cap layer (3) was approximately 10 nm, while the thickness of the NiFe main layer (2) was 50 nm. The SED ring pattern confirms the structure of NiFe and is similar to that observed using X-ray diffraction.

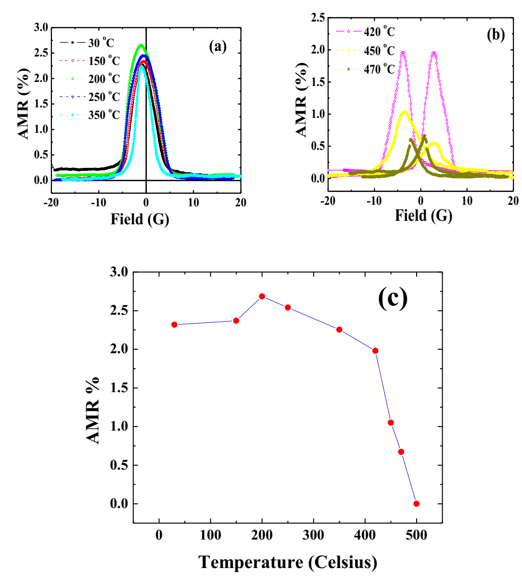

FIGURE 3. (a-b) effect of vacuum annealing on the magnetoresistance behavior of the Ta/NiFe/Ta thin film; (c) Variation of AMR ratio with annealing temperature.

Fig. 3(a-b) shows the AMR curves of Ta/NiFe/Ta films annealed in vacuum for 1 hour at different temperatures. It is confirmed that AMR value increases significantly with increasing the temperature up to 200°C and a maximum value of 2.53% was achieved as shown in Fig.3 (c). Above 200°C, from 250 to 470 °C as shown in these figures, decrease in the AMR values was observed and minimum value was 0.6% for film annealed at 470 °C. As shown in Fig..3 (a), for films annealed at temperatures from 150 to 350 °C, the AMR responses show nearly reversible parabolic behavior which indicates the coherent spin rotation as observed in nano-wires [1]. Furthermore, in Fig. 3(b), films prepared above 350 °C, all the AMR curves show hysteretic behavior with two sharp peaks, which is a typical characteristics of multidomain behavior and consistent with anisotropic magnetoresistance effect [2]. The variation of AMR with annealing temperature shown in Fig. 3(c), which shows that AMR disappears at annealing temperature ~ 500 ^{o}C .

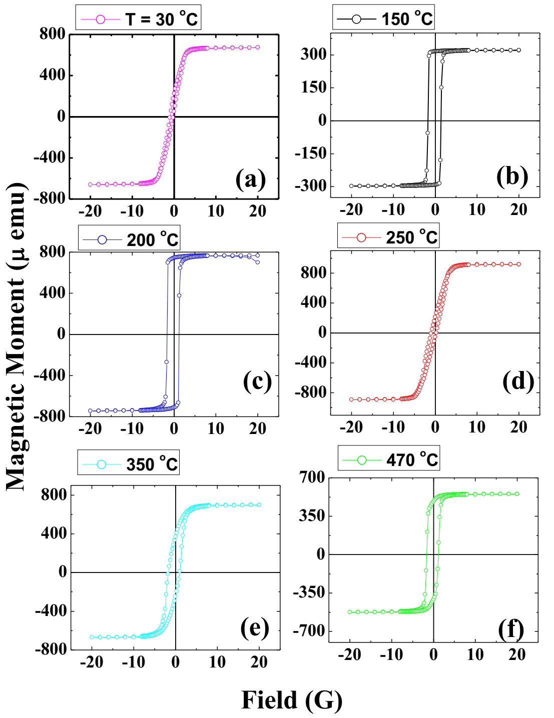

FIGURE 4. (a-f) effect of vacuum annealing on the M(H) curves of the Ta/NiFe/Ta thin film.

The measured M(H) curve for the as deposited film (at 30 ^{o}C) and the films heat treated in vacuum at 150, 200, 250, 350 and 470 ^{o}C are shown in the Fig. 4(a-f), respectively. Magnetization measurements were performed at room temperature using the vibrato sample measurement system (VSM). The M(H) curve showed the canted shape for the as deposited film as shown in Fig. 4(a), which changes into rectangular shape for the films heat treated up to 200 ^{o}C as shown in Figs. 4(b-c). While for the films heat treated from 250 to 470 ^{o}C, shows the canted shapes. The canted shaped M(H) curves are attributed due to strip domain structures which are composed of many fine magnetic domain structures [3]. However, the rectangular shaped M(H) curves observed at 150 and 200 ^{o}C confirmed the formation of single domain structures in the thin films, which are generally observed in thinner films[3] and nanowires [1] .

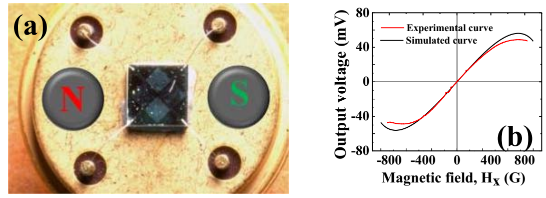

FIGURE 5. (a) sensor fabricated on a silicon substrate and externally biased by two hard magnets; (b) experimental curve along with the simulated curve.

The developed $Ni_{81}Fe_{19}$ thin film (thickness = 50nm) having Ta as a buffer layer (thickness = 10nm) was used for the AMR sensor development. Four quasi linear AMR sensors in the form of Wheatstone bridge circuit configuration were fabricated on silicon substrate as shown in Fig. 5(a). For the higher sensitivity and less power consumption in the sensor, each sensor array was patterned in the meander type shape containing 25 multi current paths. To achieve the quasi linear characteristics, each sensor array was patterned out at an angle of ± 45^o. But in this case, shape anisotropy is an important parameter, due to which the resultant sensitivity of the sensor may reduce.

As shown in Fig. 5 (a), the sensor paths are inclined at an angle, ε_o = 45^o with respect to the anisotropy axis and this configuration can result as a different resultant anisotropy axis which inclines at an angle ε instead of ε_o . Due to this anisotropy axis deviation by an angle of $\Delta\varepsilon = (\varepsilon_o - \varepsilon)$, the quasi linear transfer output for this type of AMR sensor geometry can be diminished by a factor of *sin* $2\varepsilon_o$ *cos* $2\Delta\varepsilon$ and the resultant quasi linear output (for $H_x < 0.5\, H_k$) for the design as shown in Fig. 5 (a) can be written as:

$$U_{out} = 2J\Delta\rho L \sin 2\varepsilon_o \cos 2\Delta\varepsilon \frac{1}{H_k + H_y \cos \Delta\varepsilon} H_x$$

This equation gives the linear output transfer characteristic and the corresponding sensitivity of the sensor is given as,

$$S = \frac{U_{out}}{H_x}$$

MATLAB code for the simple patterned AMR sensor was generated successfully for the output transfer characteristic equation and the simulation was performed for the optimized sensor parameters, which along with the simulated output results are given below as follows:

Constant parameters:

[1] Material constants:

Resistivity of the Permalloy thin film, $\rho = 220\times10^{-9}$ Ωm

Maximum resistivity change, $\Delta\rho/\rho = 2.5\%$

Magnetization saturation, M_S = 24 Gauss

Material Anisotropy field, $H_{ko} \approx 20$ Gauss

Thickness of the Permalloy thin film = 60 nm

[2] Sensor design parameters:

Total length of the current path strip in the AMR sensor, L = 1000 μm;

Width of the AMR sensor current path strip, w = 20 μm

Gap between two current paths, p = 20 μm

Total area of the sensor, A = 1 mm^2

Total number of current paths, N = 25

Total resistance of the sensor in the bridge circuit = 4.67 kΩ

Current density feed to the bridge circuit, $J = 1.1157\times10^9$ A/m^2 (for I = 1.1157 mA)

Applied measuring field, H_X = -1000 to +1000 Gauss

[3]MATLAB simulated Output values of the AMR sensor:

Value of total anisotropy field, $H_k = H_{ko} + H_d + H_{Bo}$ = 1020 Gauss

Operating field range, H_X = -1000 to +1000 Gauss

Sensitivity, S = -56.1 to 56.1 mV/V/Gauss

Maximum operating voltage = 6.259 V

Hence for the optimized sensor parameters, the sensor was. 5(a). For the fabricated sensor, prior to find out the quasi linear transfer characteristic, the experimental characterization was performed. To stabilize the sensor (so that to achieve a very low hysteresis, high linearity and high sensitivity), two hard magnets having opposites magnetic poles were fixed nearby the main sensor as shown in Fig. 5(a). The optimized position of both the magnets was 1 cm (i.e., the distance between the centers of the magnet and sensor). Fig. 5 (b) shows the experimental output voltage along with the simulated output for the developed AMR sensor. Both the curves show a good agreement at lower fields, however it shows a deviation at higher fields.

In conclusion, we have deposited Permalloy thin films on Si/SiO_2 substrates and both the structural and magnetic properties were investigated as a function of annealing temperature. It was observed that the films annealed in the temperatures ranges from 150 to 250 ^{o}C were shown highest AMR percentage (2.53 %) with single domain characteristics and very useful for the development of AMR based magnetic field sensing devices. Magnetoresistive sensor with Wheatstone bridge configuration are fabricated and the linear output characteristics was found to match qualitatively with simulated data.

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